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Transport Current Distribution of a SmBCO Coated Conductor

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Abstract-- **The transport current distribution across the tape width of a SmBCO coated conductor was investigated. The current distribution was estimated by applying an inversion process to the field distribution measured in the vicinity of the tape by using a scanning Hall probe method. The obtained result is well consistent with one predicted by the Bean model, however, at the edges the current are not constant and do not generally plateau, on the contrary.**

1. INTRODUCTION

Since technology of developing long length coated conductors has been achieved, their application to ac power devices is more promising. AC loss is one of the most important factors for the performance of superconducting power devices. The current distribution in coated conductors has an impact on their ac losses.

There are many efforts to understand and visualize the current distribution of superconducting films. Brandt and Indenbom [1] calculated analytically a current distribution of superconducting strip with transport current, which is based on the Bean critical state model. Johansen et al [2]. solved the inversion problem for a single crystalline superconducting film with strip geometry using the magneto optic image (MOI), and their results of underlying current distribution showed good agreement with the Brandt and Indenbom's calculation. The inversion method has been improved using an iterative process, and gives more accurate current profiles at sample's edges [3-4]. However, since the MOI was generally taken at 10 K, it is not so useful in the practical point of view: the current distribution at 77 K will be different. Amemiya et al [5]. used the magnetic knife method to measure the lateral critical current distribution in an $YBa_2Cu_3O_7$ based coated conductor; however, the results are unclear. Polak et al [6]. also obtained current distribution of a $DyBa_2Cu_3O_7$ coated conductor using an inversion matrix relating the discrete mesh of the current and the discrete mesh of the measured field data, applying the Tichonov regulation [7-8]. They used the scanning Hall probe method to map the field across the tape width. The calculated current are unclear: even outside the sample there was current, and they did not give sufficient explanations for the profiles themselves, which look different from those of the single- crystalline film.

We have successfully obtained the current distribution, using Johansen's inversion method with the iteration process from our field distribution data of SmBCO coated conductor in a perpendicular magnetic field [9-10]. In this report, we studied the current distribution in the SmBCO tape with transport current.

2. EXPERIMENTS

The $SmBa_2Cu_3O_7$ (SmBCO) tape was fabricated on the biaxially textured IBAD template. The thickness of the SmBCO film was 2.2 μm which was deposited by coevaporation method [11-12]. Then a 5 μm thick Ag film was deposited. The width and the length of the tape were 4 mm and 30 mm, respectively. The critical current, I_c, was 176.3 A at 77K, self –field. The sheet current is 440.75 A/cm. The schematic diagram of our scanning Hall probe (SHP) system is shown in Fig.1. The Hall probe was an AREPOC product. The detailed explanations are in the text. The magnet is 90 degrees out of view. It was supported by a spring bar at the end of a 40 cm long ceramic stick positioned with a 3-axis positioner. We scanned the probe across the tape width (x-direction).

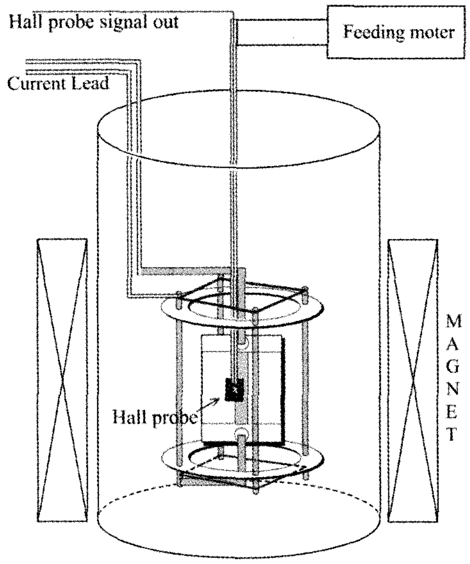

Fig. 1. Schematic diagram of the scanning Hall probe measurement system.

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The active area of the probe was 100 μm × 100 μm and positioned at approximately 350 μm inside the probe body. The surface of the tape was covered by a 50 μm thin Mylar tape. The frontal side of the Hall probe touches the surface of the Mylar tape and slides on it during scanning. Hence, the total distance, δ between the active area of the probe and the tape was about 400 μm. The tape and the Hall probe were in liquid N_2.

We measured the distributions of the normal component (z-direction) of fields, $H(x, I_a)$, near the surface of the SmBCO tape using the scanning Hall probe method. The transport current was applied from 0 to 120 A in about 20 A-steps. From the measured filed distribution data, we obtained the current distribution applying the iterative inversion method [2-4], [9-10].

The inversion method described briefly below: The normal component of the magnetic field at a distance δ above a superconducting strip is related to the current density distribution by the Bio-Savart's law [1]

$$H(x, I_a) = \frac{1}{2\pi}\int_{-w}^{w} \frac{(x-x')J(x', I_a)}{(x-x')^2+\delta^2}\,dx' \qquad (1)$$

where $2w$ is the width of the tape, d is the thickness of the SmBCO fillm, and $J(x) = \int_{-d/2}^{d/2} J(x,z)dz$ (sheet current, in units of A/m like H_a).

Johansen et al. [2] give the solution of $J(x)$;

$$J_0(n) = \sum_{n'} \frac{n-n'}{\pi}\{\frac{1-(-1)^{n-n'}e^{\pi k}}{k^2+(n-n')^2} + \frac{[k^2+(n-n')^2-1]}{[k^2+(n-n'+1)^2]}\frac{[1+(-1)^{n-n'}e^{\pi k}}{[k^2+(n-n'-1)^2]}\}\times H_0(n') \qquad (2)$$

The iteration process was developed [3-4] in order to improve the accuracy at sample's edges: $J(x) = \sum_{m=1}^{n} J_m$ calculated on the n-th iteration step is set equal to zero outside the superconducting film, and substituted into equation (1) to obtain the field profile $H_n(x)$. Substituting the difference of $H(x) - H_n(x)$ into equation (2), they calculate the (n+1)-th compensating current $J_n(x)$. They then set $J(x) = J(x) + J_n(x)$ and start the next iteration. After N iterations, the erroneous field, $H(x) - H_N(x)$ becomes infinitesimal, then the correct current profile can be obtained as

$$J(x) = \sum_{n=1}^{N} J_N \qquad (3)$$

Once we know the current distribution, we can know the flux density distribution, $B(x) = \mu_0 H(x)$, by substitution of equation (3) into equation (1) at any δ.

3. RESULTS AND DISCUSSIONS

The field distribution is shown in Fig. 2 and the corresponding sheet current distribution is shown in Fig. 3 (a). We measured the field distribution at a little far from the tape surface, so we calculated $B(x)$ at δ =40 μm using the calculated sheet current distribution in Fig 3 (a) and equation (1). δ =40 μm is the lowest value that gives no numerical error in our calculation program.

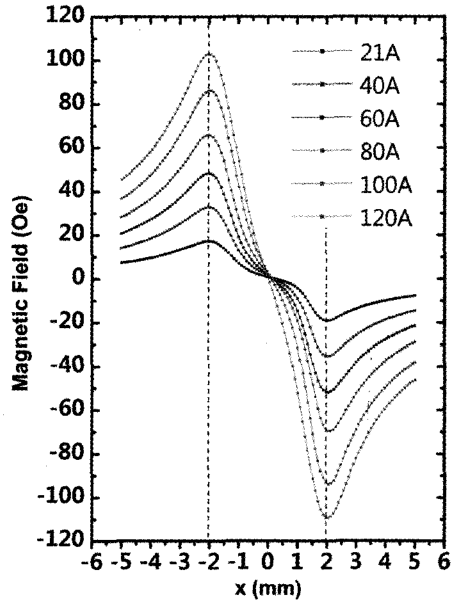

Fig. 2. Normal component of the field distribution, $H(x, I_a)$, measured at δ =400 μm across the tape width. The dashed lines indicate the sample edges. I_a = 21, 40, 60, 80, 100, and 120 A were applied.

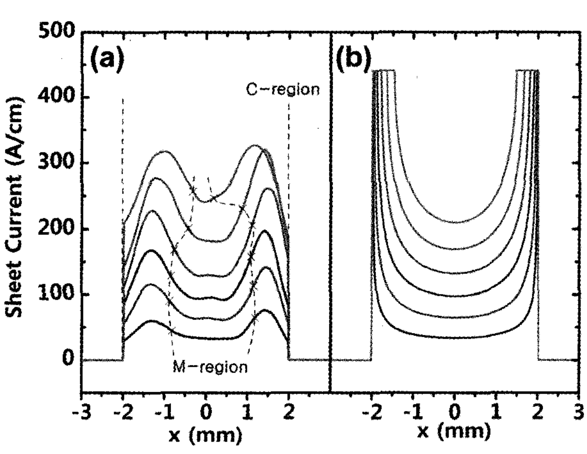

Fig. 3. Current distribution obtained (a) by the inversion of Fig. 2, (b) from the Brandt's analytical calculation.

Fig. 4 (a) showed $B(x)$ calculated. For comparison, the Brandt and Indenbom's results of $J(x)$ and $B(x)$ [1] are shown in Fig. 3 (b) and Fig. 4 (b), respectively. Brandt and Indenbom calculated $J(x)$ and $B(x)$ analytically based on the Bean's critical state model, where critical current is assumed to be constant. Their results reveal that the critical current flows in the flux-penetrated region, which is the critical state region (C-region). In the flux-free region, i.e. the Meissner region (M-region), there is the shield current. We found the front positions of the flux penetrated in the SmBCO film in Fig. 4 (a), which are summarized in Table I. The flux penetrated into the SmBCO tape further inside than predicted by Brandt and Indenbom shown in Fig. 4 (b). M-region is between b_L and b_R. C- region is between b_R (b_L) and the sample edge, 2 mm (-2 mm), which are marked by the dashed lines in Fig. 3 (a).

The values of the shield current distribution in $J(x, I_a)$ shown in Fig. 3 (a) are in rather good agreement with the Brandt calculation. However, $J(x, I_a)$ in the C-region reveals the significant difference compared with Fig. 3 (b): the maximum value of $J(x, I_a)$ iss not constant, instead, increased with increasing the transport current.

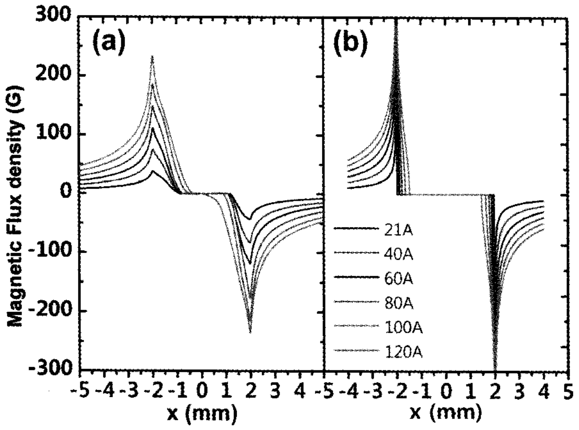

Fig. 4. Flux density distribution calculated (a) by substituting the current distribution in Fig. 3 (a) for equation (1), (b) the Brandt's analytical calculation [1].

TABLE I
FRONT POSITION OF THE PENETRATED FLUX.

Current(A)	b_L(mm)	b_R(mm)
21	-0.83	1.17
40	-0.89	1.15
60	-0.85	1.09
80	-0.76	1.11
100	-0.44	0.87
120	-0.33	0.17

We think that the two distinguished features - (1) the flux penetrates further inside from the edges, (2) the maximum value of $J(x, I_a)$ is not constant - are attributed to the coarse granular structure of the coated conductor. In the granular structure, the film is composed of many grains, so there are many boundaries. The magnetic flux can more easily penetrate along the grain boundaries. The inhomogeneity was not taken into consideration in the theoretical calculation. There was also flux-free region even in the C-region of the SmBCO coated conductor since the flux penetrated along the grain boundaries. If a gain can be considered as a single crystal, then the flux could penetrate form the grain boundaries into the grain, which resulted in the flux empty region in the grain of the C-region before the transport current reached the critical current. There was the shield current flow in the flux empty region, of which value is lower than the critical current. For that reason, the maximum value of $J(x, I_a)$ was not constant and lower than the critical sheet current. There are also other reasons depending on sample properties. For an example, the stoichiometry difference in the grains can result in the inhomogeneous distribution of $J(x, I_a)$.

4. SUMMARY

We measured the field profiles, $H(x, I_a)$, near the surface of the SmBCO coated conductor with transport current, I_a. From the normal components of the measured field profiles, the corresponding sheet current profile, $J(x, I_a)$, was obtained by applying the numerical iterative inversion method. It was found that the values of $J(x, I_a)$ in the C-region are inhomogeneous and increased with increasing I_a. We think that this feature was due to the mixture of shield current and critical current in the granular structure of the sample.

ACKNOWLEDGMENT

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